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Experimental Investigation of the Separated Flow Past Slender Bodies in the RAE 5 Metre Low-Speed Pressurised Wind Tunnel

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SUMMARY

Tests carried out on a cone-cylinder model in the 5 metre low-speed wind tunnel have provided examples of the pressure distribution near the nose in conditions where significant values of side force occur, showing how this is dependent on roll angle of the nominally axially-symmetric body. At values of roll where the side force is at its maximum, comparison of the measured pressure distribution with that predicted theoretically, using an inviscid mathematical model of the separated flow past a slender cone, shows that the major features of the flow are identified reasonably well by the inviscid model and that the development of the side force at least in its major features can be described without the need for appeal to any additional viscous interaction. Further work, however, will be necessary to identify the mechanisms giving rise to intermediate values of side force.

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1 INTRODUCTION

This Memorandum describes preliminary results obtained in the RAE 5 metre tunnel as part of a fundamental investigation of the low-speed separated flow about slender bodies at high incidence. In particular, attention has been focused on the generation of high levels of side force on axially symmetric bodies placed at high incidence. The definition of the experimental programme has been guided by the earlier experimental work of Mundell[1] and the theoretical work of Fiddes and Smith[2].

2 DESCRIPTION OF MODEL

The model used in the preliminary experiments was a cone-cylinder combination, comprising a nose cone of 10 degrees semi-apex angle faired to a cylindrical afterbody. The total length of the model was 2.26 metres, and its diameter 0.297 metre. The other details of the model are given in Fig 1. The nose section of the model was pressure-tapped at six longitudinal stations, with each station housing 36 circumferential holes placed 10 degrees apart. The design of the model allowed pressures to be measured simultaneously at two stations, though results will be presented here for the foremost station only. The initial experiments have concentrated on the nose portion of the model as this is known to have the strongest influence on the development of side force at high incidence. The model was fixed to a sting and quadrant via a roll box, and could be rolled through 360 degrees. Force measurements for the complete model have been presented by J.S. Smith[3].

3 EXPERIMENTAL TECHNIQUE

The model was pitched to a particular incidence (20, 25, 30 or 35 degrees) with the model at zero roll, and the pressures measured at two stations. The model was then rolled, typically in 10 degree intervals, and pressures recorded again. The pressures were integrated to give local side- and normal force coefficients in 'unrolled' body axes, *ie* normal force in the incidence plane. This conversion of pressures to force coefficients was performed by an online computer system, so that roll angles giving high side-force levels could be found quickly and examined in detail.

4 RESULTS

Results are presented here for the front station only, 0.15 metres from the apex of the model, for a freestream Mach number of 0.15 and Reynolds number of 3.7 million per metre. An earlier investigation of the boundary layer state, using the china-clay technique[4] revealed that the boundary layer was laminar at the first pressure measurement station for the range of incidences considered in this experiment.

Fig 2a-d show the variation of local side- and normal force coefficients with roll angle for the three incidences used in the test. At the lowest incidence, 20 degrees, little side force is visible, though normal force variations are clearly present. At 25 degrees incidence, side forces of either hand are present, some 180 degrees apart in roll. By 30 degrees incidence, the level of side force has increased, as has the variation in normal force. At 35 degrees incidence, there is a large variation of side-force, but the largest values of C_y occur at the roll angles where side force first becomes apparent at the lower incidences.

To examine in detail the pressure distributions giving maximum side force, Fig 3 shows a typical example for 35 degrees incidence, with some salient features annotated. Points to note are:

(i) the maximum pressure (attachment, A) position is offset from the windward generator;

(ii) a small amount of pressure recovery takes place before separation. Separation is inferred to occur at the points labelled S1 and S2;

(iii) only one suction peak (P), associated with a vortex core lying near the surface of the cone, is visible.

To illustrate just how typical of the maximum side force cases this pressure distribution is, Fig 4a&b show a compilation of the pressure distributions giving maximum side force from the whole roll-angle range. It is apparent that they have the same characteristic features as the pressure distribution shown in Fig 3. To complete the comparison of the pressure distributions, Fig 5 shows the pressure distributions which are appropriate to the absolute maximum positive C_y and to the maximum negative C_y, with, in this second case, the pressures being plotted against the complementary angular position, (360-theta) degrees. The two pressure distributions are seen to be identical. It thus appears that the high side-force state is associated with a characteristic circumferential pressure distribution that is practically independent of roll angle apart from a change in handedness. Also of note are the large differences in pressure field ahead of separation between the left and right sides of the model; it is these that give rise to the major proportion of the side-force. The only visible suction peak associated with a vortex core acts on the upper surface of the cone and contributes little to the side force.

The maximum side-force state does not appear to be associated with a large asymmetry in separation position. Fig 4a&b show little variation in separation position, and the difference in separation position between port and starboard sides does not exceed 15 degrees.

These results indicate that the mechanism for generation of large side-forces in this experiment is inviscid in origin. A viscous mechanism, for example model surface imperfections leading to different boundary layer development on either side of the attachment line, would be expected to give a wider range of separation positions. Furthermore, a mere perturbation of the separation positions is not sufficient to produce large side-forces - there must be a marked perturbation of the inviscid flow component, *eg* the vortex core locations. This supports the conclusions of Ref 2, where it is demonstrated, using a mathematical model of the separated flow past a slender cone, that above certain incidences non-unique solutions are possible for the position of the vortex cores (and their associated feeding sheets) for given separation positions. Fig 6 shows two solutions obtained for the case equivalent to a cone of 10 degrees semi-apex angle at an angle of incidence of 36 degrees with separation positions some 14 degrees different on each side, *ie* the order of perturbation of separation position found in this experiment. The 'first family' solution represents a weakly perturbed symmetric flow solution, and gives low side-force. The 'second family' solution represents an alternative solution described in detail in Ref 2. It gives side-forces of a magnitude comparable to those measured in the experiment. Fig 7a shows the theoretical pressure distribution corresponding to the first family solution. Of note are the two suction peaks associated with the two vortex cores (though the suction levels are over-estimated by the theory of Ref 2). Fig 7b shows the pressure distribution from the second family solution. While there is plainly a substantial error in suction level under the vortex core given by the theory, it is seen nevertheless that the salient features of the high side-force pressure distributions observed in the experiment are present. The core lying near the surface of the cone induces the large suction peak while the remote core appears to have little effect on the pressure distribution.

Although the high side-force states may now be explained in terms of steady, inviscid flows as described in Ref 2, the intermediate side-force levels require explanation. Fig 8a-d show the variation in circumferential pressure distribution as the roll angle is changed from 100 degrees to 130 degrees. During this roll angle variation the side-force changes sign and moves from a large positive C_y to a large negative C_y. The intermediate pressure distributions show a regular variation from one state to the other. The question then arises as to the nature of the mechanism which gives rise to these intermediate states. Three possibilities suggest themselves:

(a) they are additional solutions of Ref 2 which have not yet been identified;

(b) viscous effects may so modify the inviscid theory that additional solutions then become possible;

(c) the steadiness of the intermediate states is only apparent and the measured pressure distributions represent a mean as the flow switches rapidly between the left-handed and right-handed states.

Later measurements by Rae[5], as yet unpublished, using rapid response pressure transducers fitted to the same model, have established conclusively that the intermediate states are reasonably steady and do not arise simply as a result of the response of the pressure measuring system to a rapidly oscillating flow.

5 CONCLUSIONS

The pressure measurements reported here have shown that on a conical nose at a given incidence, the high side-forces are produced by a characteristic pressure distribution that is practically independent of roll angle. The high side-force state is not a result of gross differences in separation position of the port and starboard primary separation lines. Furthermore, the high side-forces are not produced by the suctions induced under a vortex core, but mainly by a port-to-starboard pressure difference ahead of separation.

Further work is needed to identify the nature of the flow giving intermediate levels of side-force.

Acknowledgments

The assistance of Mr D G Dobney in the conduct of these experiments is gratefully acknowledged.

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No.	Author	Title, etc
1	A.R.G. Mundell	RAE Unpublished (1982)
2	S.P. Fiddes J.H.B. Smith	Calculations of asymmetric separated flow past circular cones at large angles of incidence. Paper 14 in 'Missile Aerodynamics', AGARD CP-336 (1982)
3	J.S. Smith	Preliminary tests on slender bodies in the 5m pressurised low-speed wind tunnel. RAE Technical Memorandum Aero 1973 (1983)
4	I.R.M. Moir	Recent experiences in the RAE 5 metre wind tunnel of a china-clay method for indicating boundary layer transition. RAE Technical Memorandum 2007 (1984)
5	A.J. Rae	RAE Unpublished (1990)

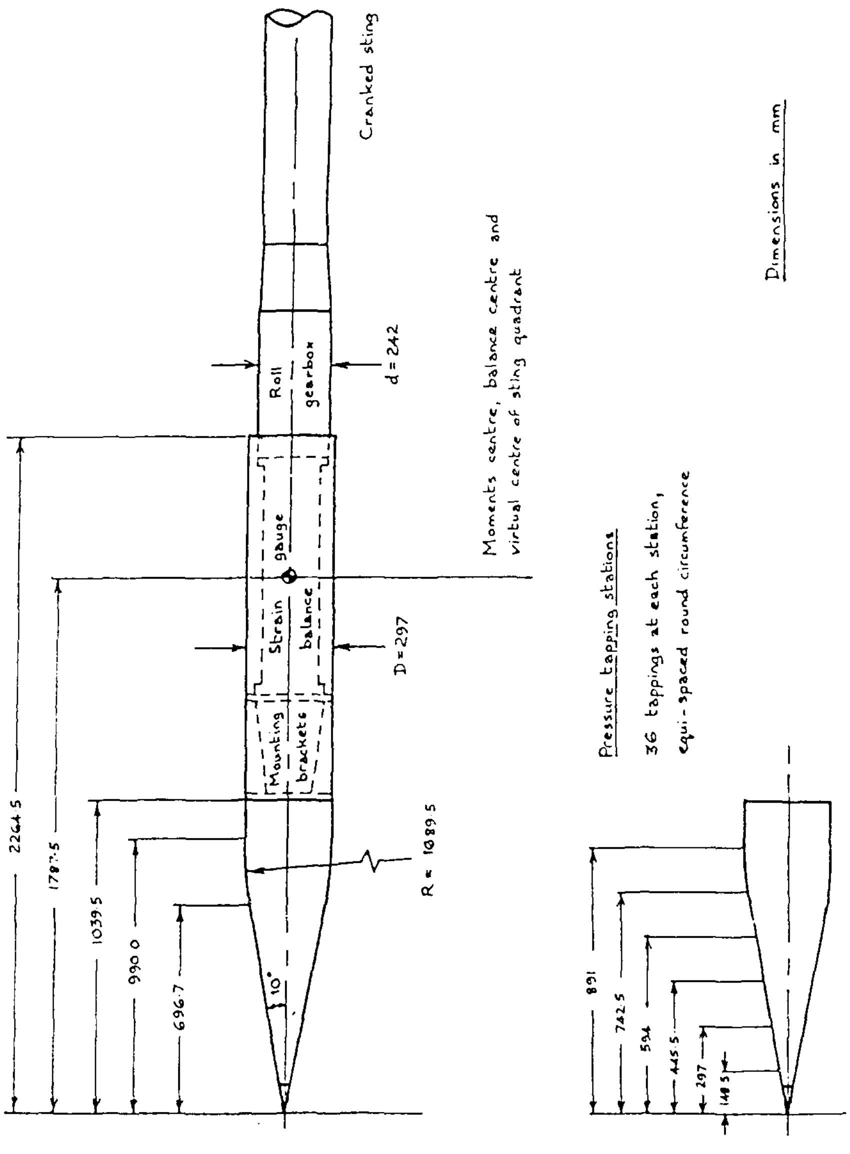

FIGURE 1 Details of cone-cylinder model

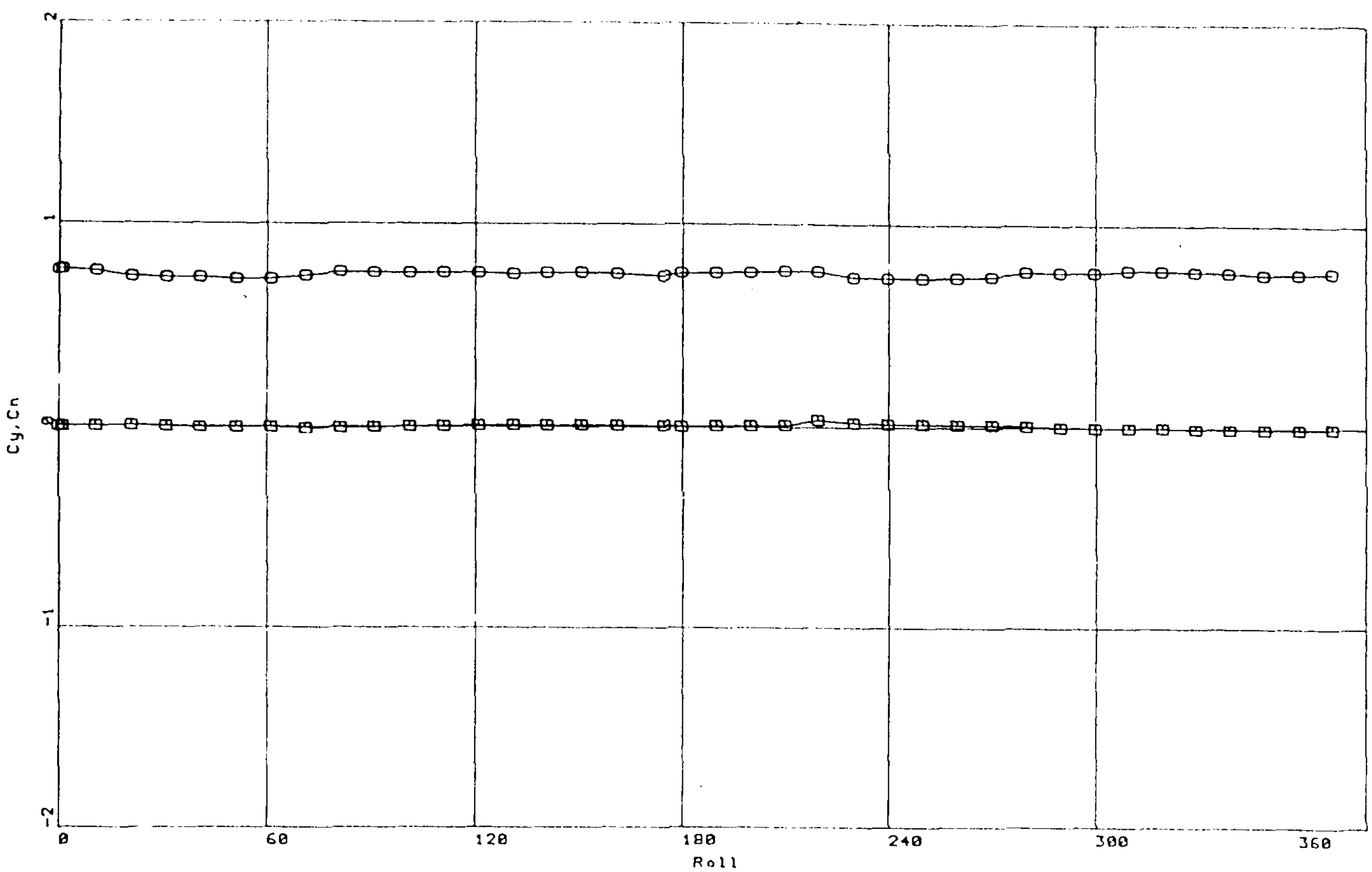

FIGURE 2a Variation of side and normal force with roll angle
Incidence = 20 degrees

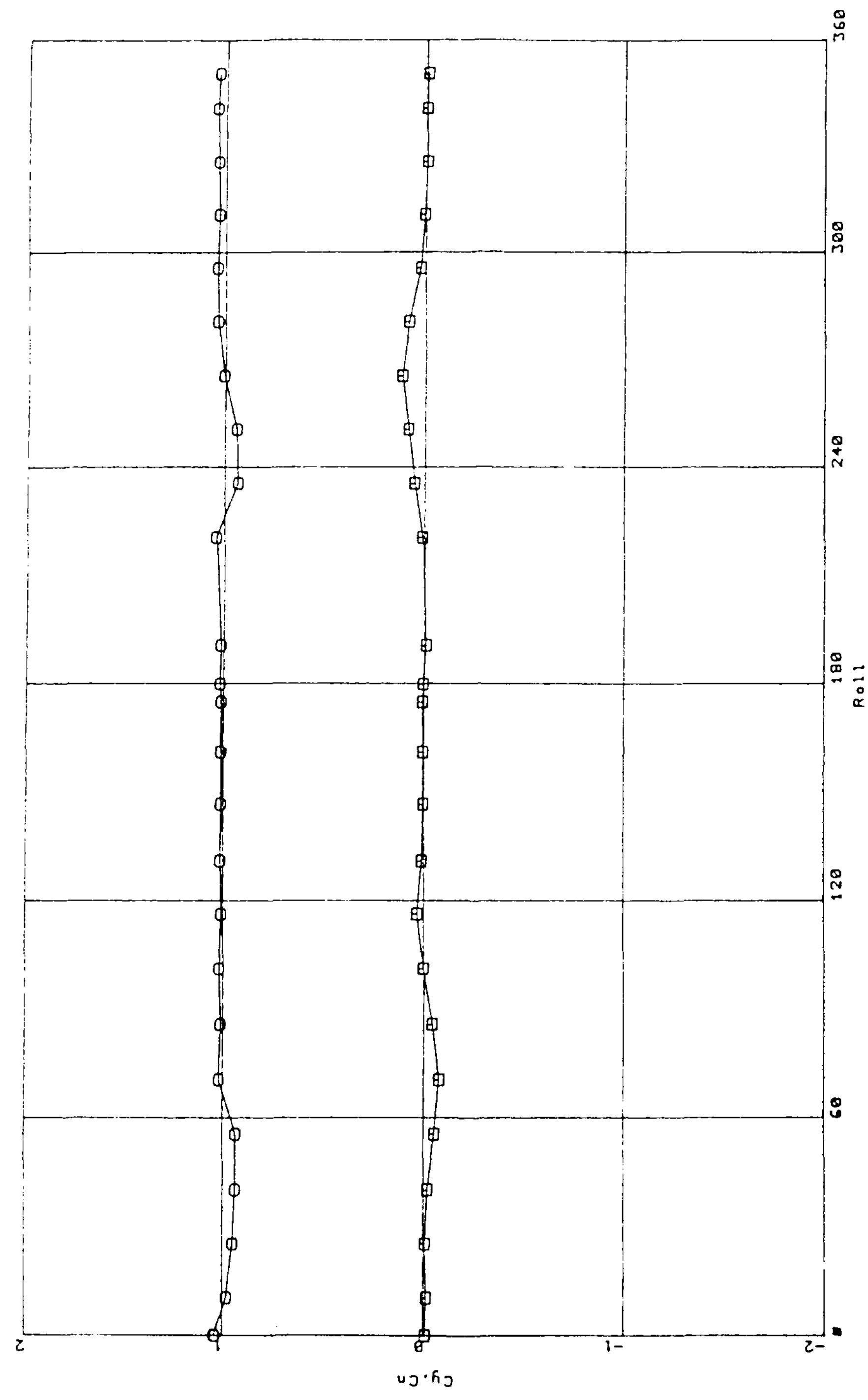

FIGURE 2b Variation of side and normal force with roll angle
Incidence = 25 degrees

Fig 2c

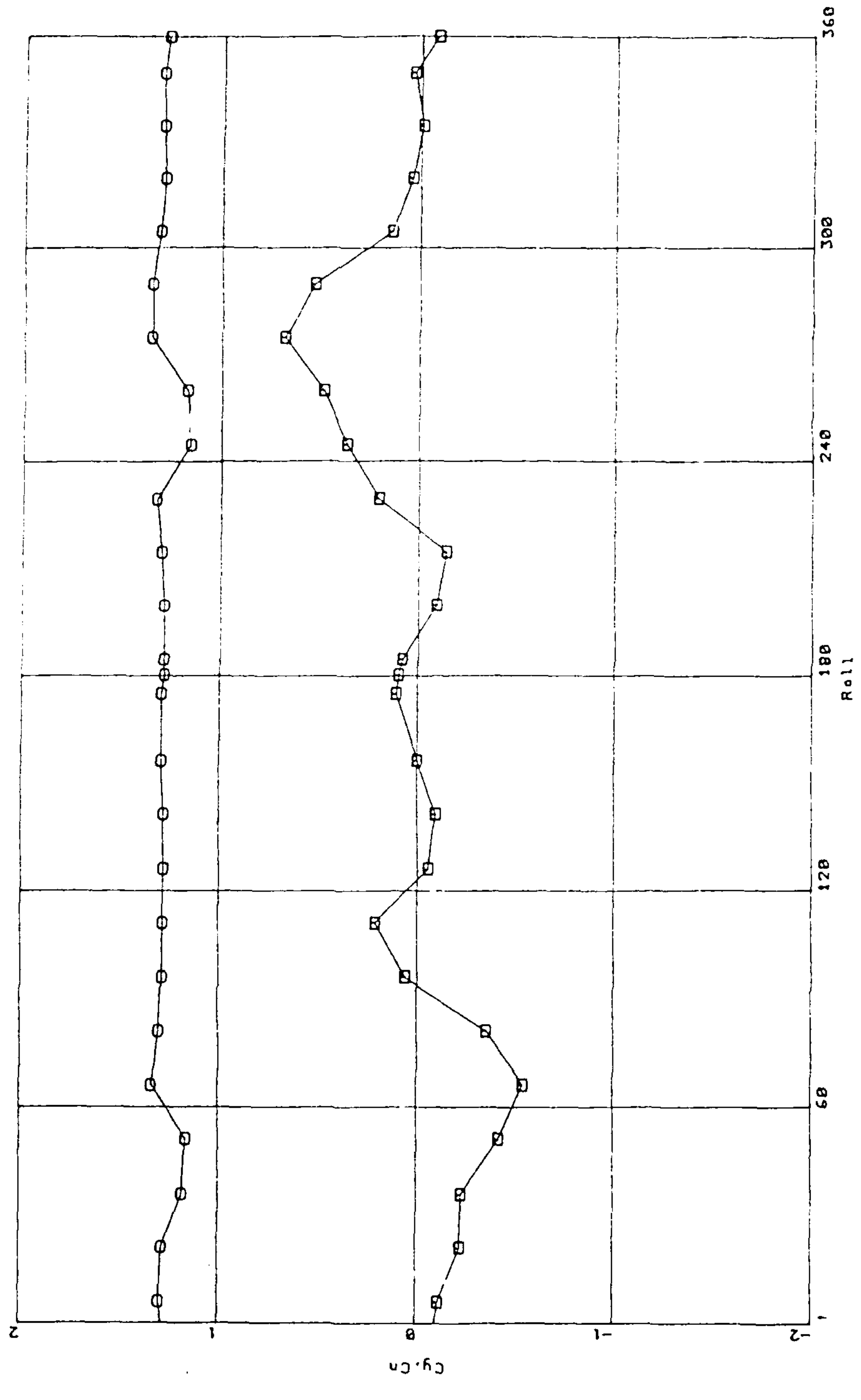

FIGURE 2c Variation of side and normal force with roll angle
Incidence = 30 degrees

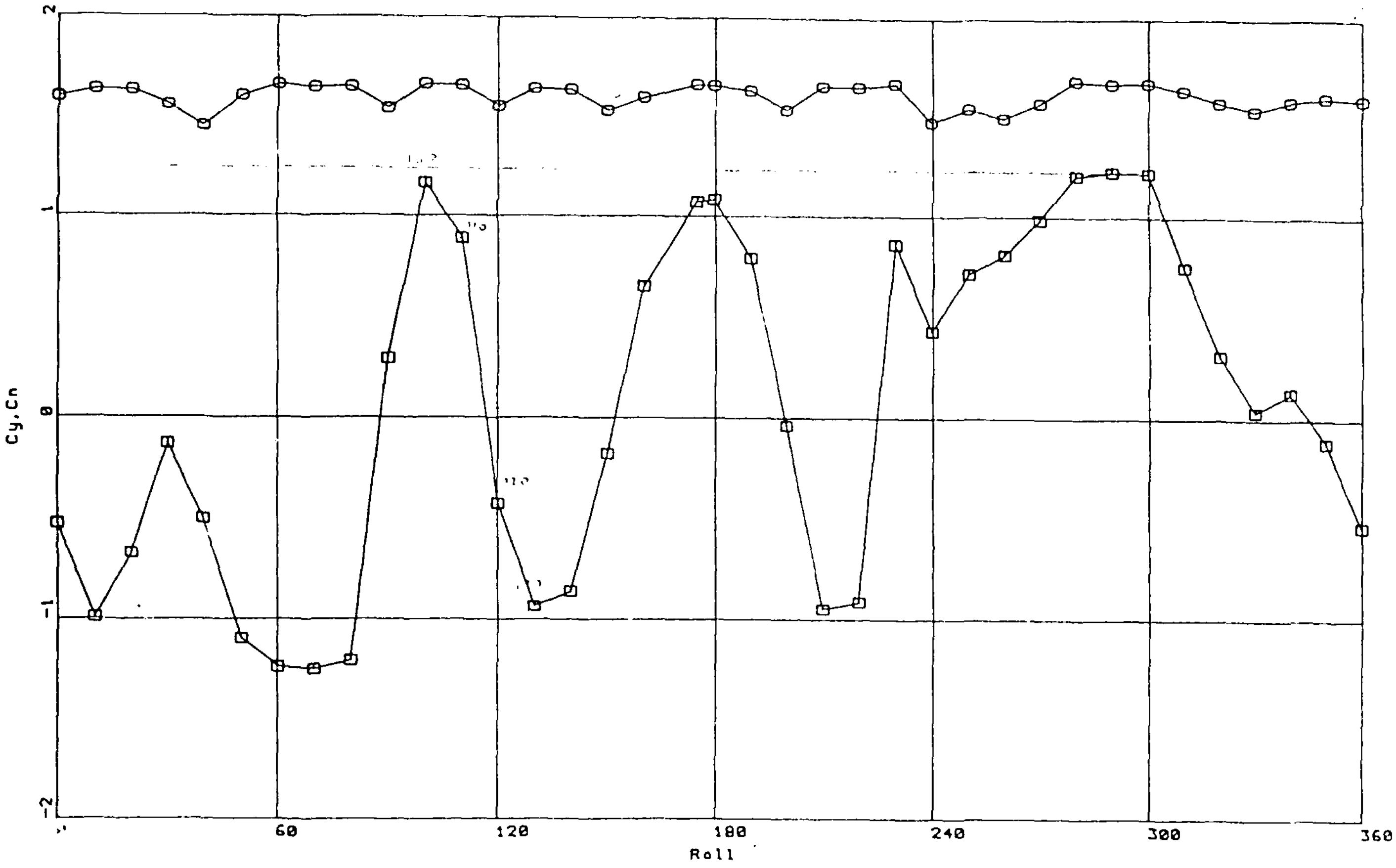

FIGURE 2d Variation of side and normal force with roll angle
Incidence = 35 degrees

Fig 3

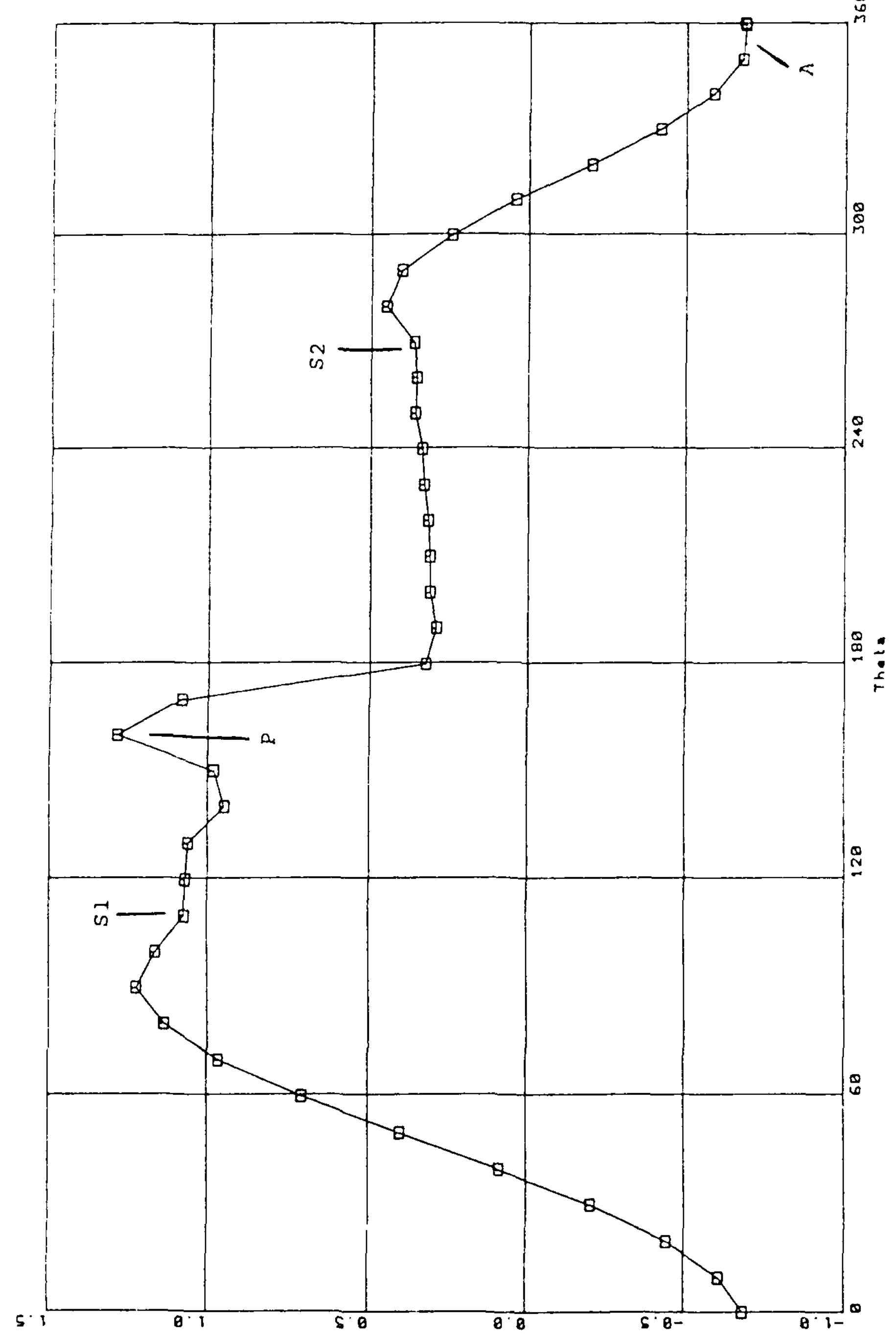

FIGURE 3 Circumferential pressure distribution giving large side-force
Incidence = 35 degrees, Roll = 290 degrees

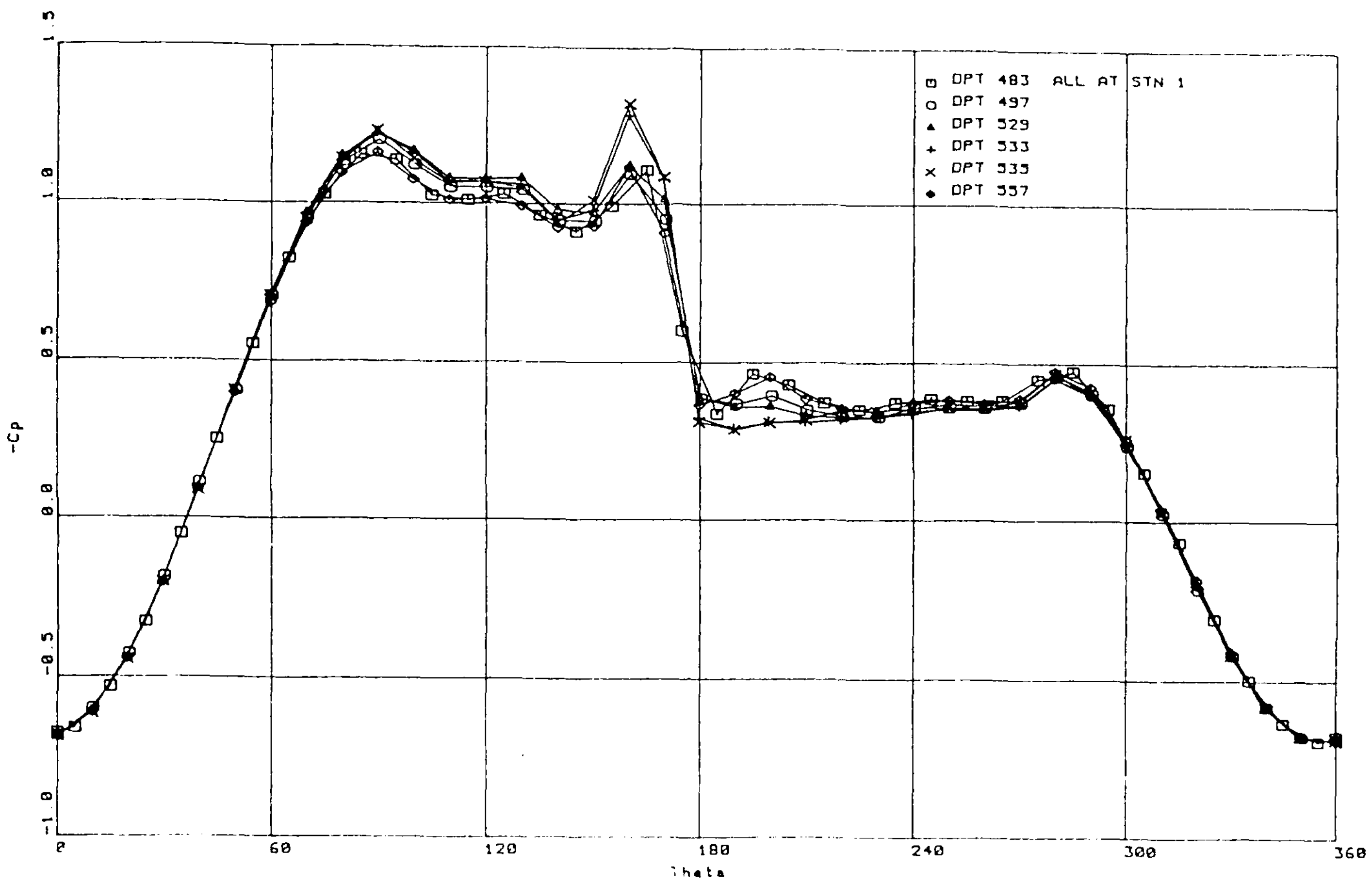

FIGURE 4a Circumferential pressure distributions giving largest +ve CY
Incidence = 35 degrees, Roll = 100,175,180,280,290,300 degrees

Fig 4b

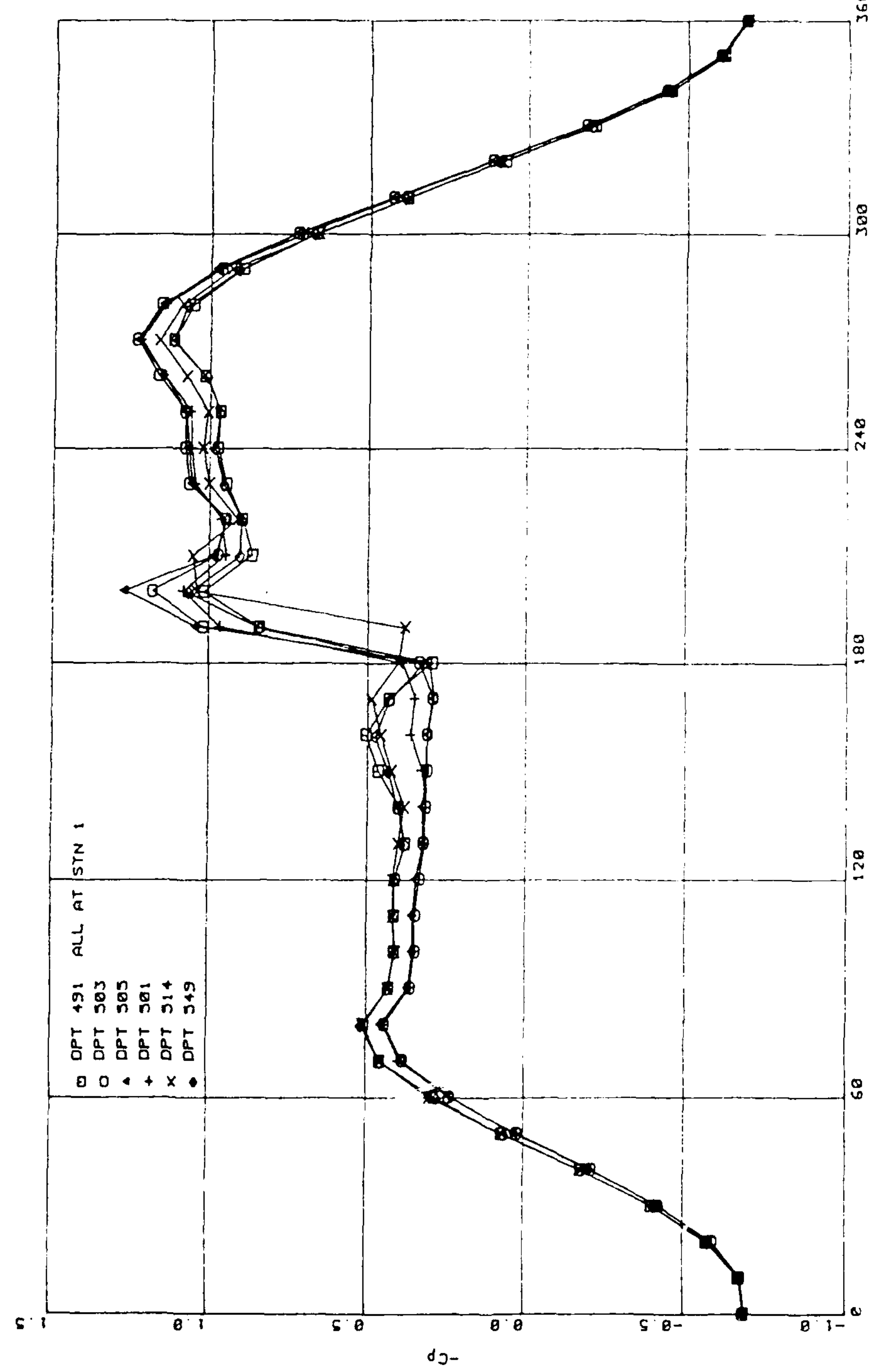

FIGURE 4b Circumferential pressure distributions giving largest -ve CY
Incidence = 35 degrees, Roll = 10,60,70,80,130,210 degrees

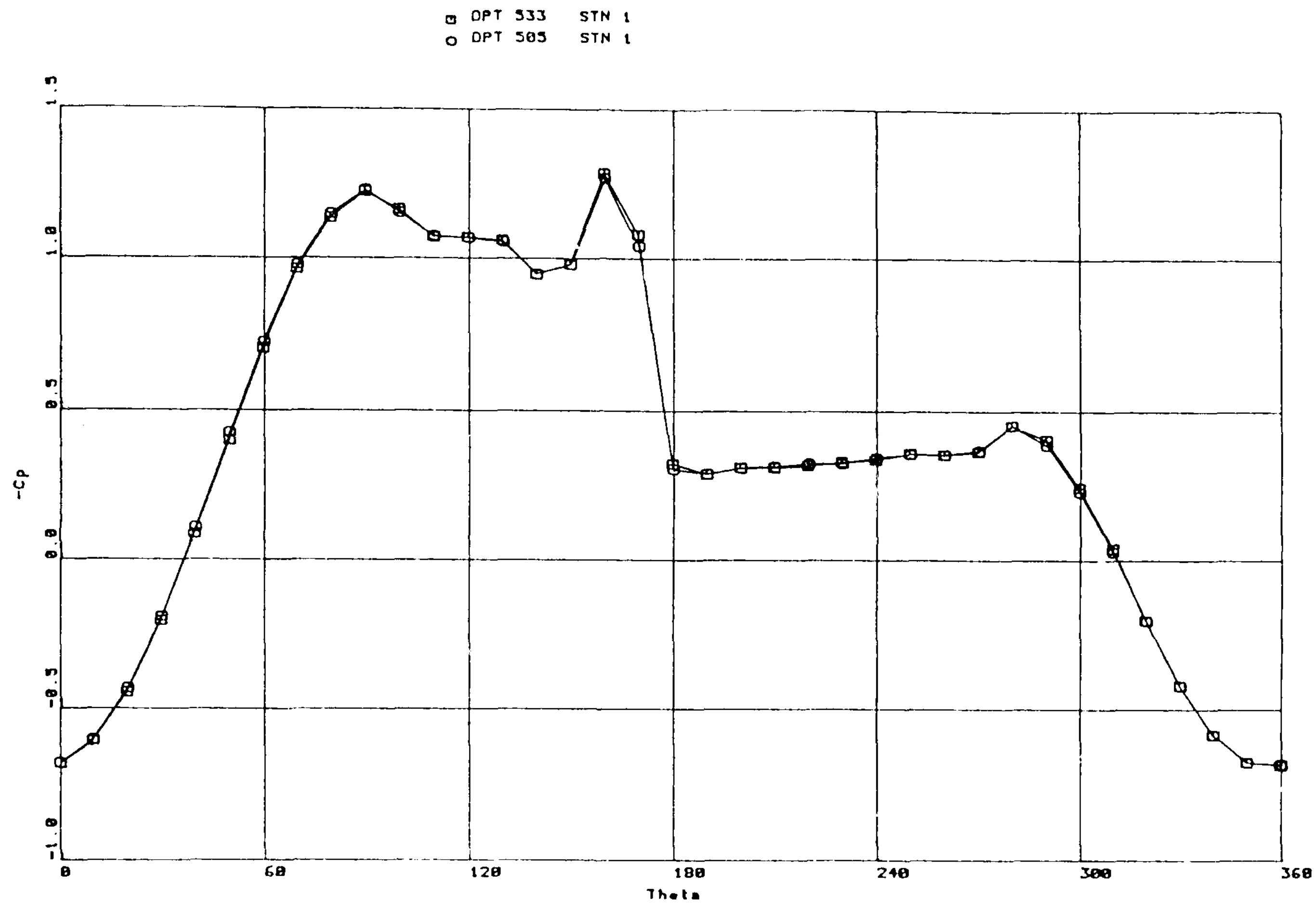

FIGURE 5 Overlay of pressure distributions for maximum -ve and +ve CY
Incidence = 35 degrees, Roll 60 and 290 degrees

Fig 6

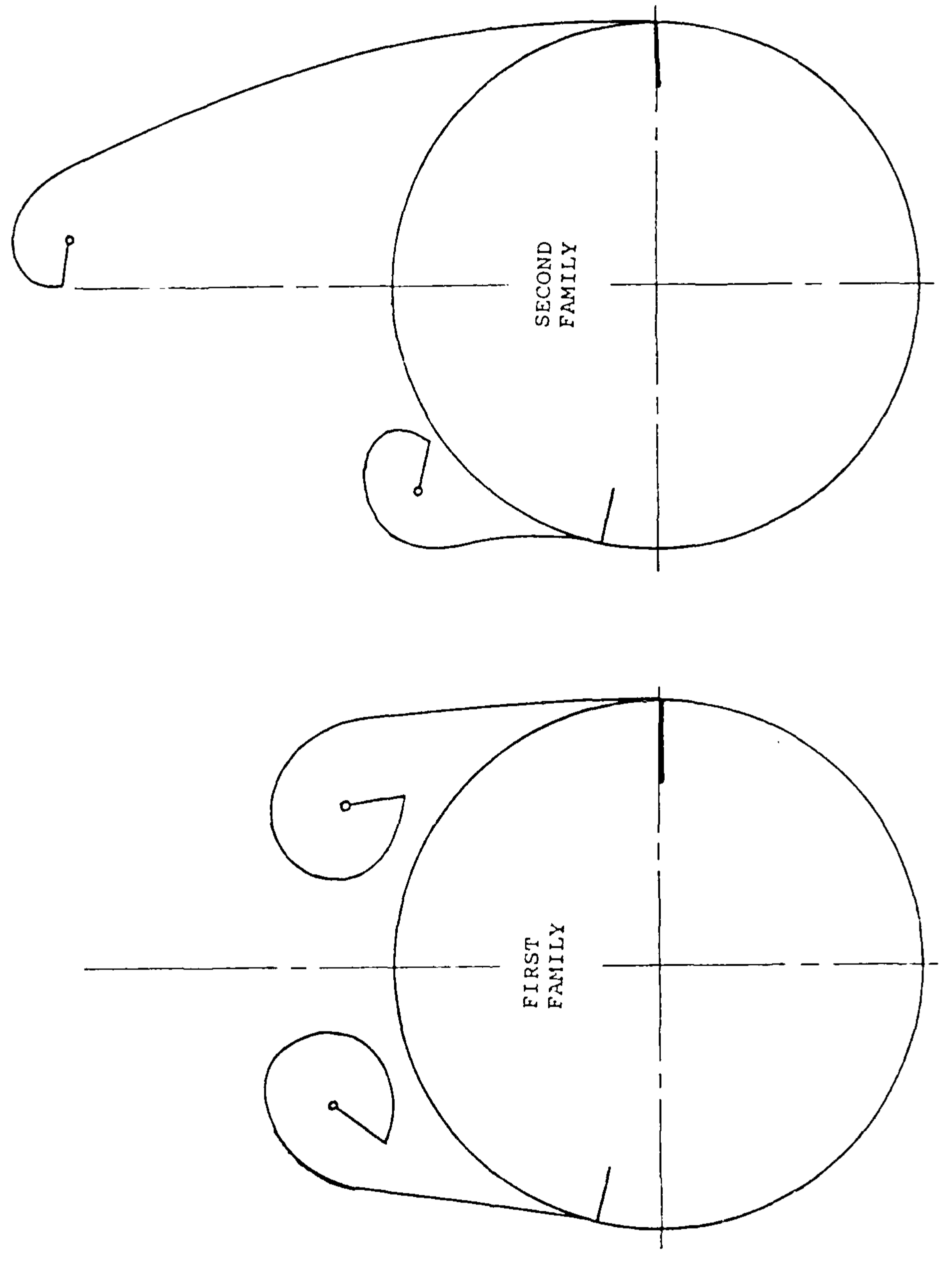

FIGURE 6 Vortex sheet solutions for 36 degrees incidence

Fig 7a

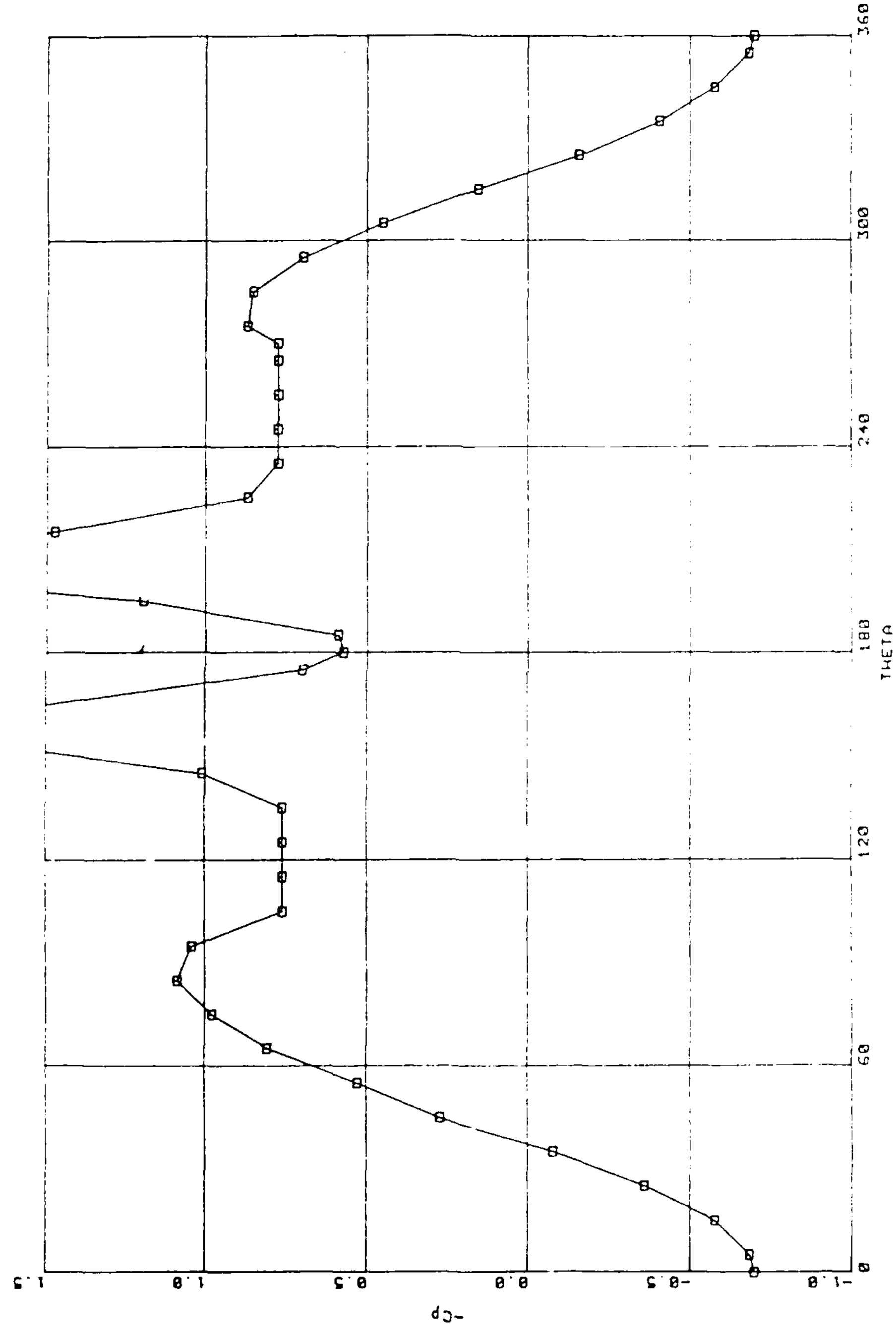

FIGURE 7a Circumferential pressure distribution for 1st family solution

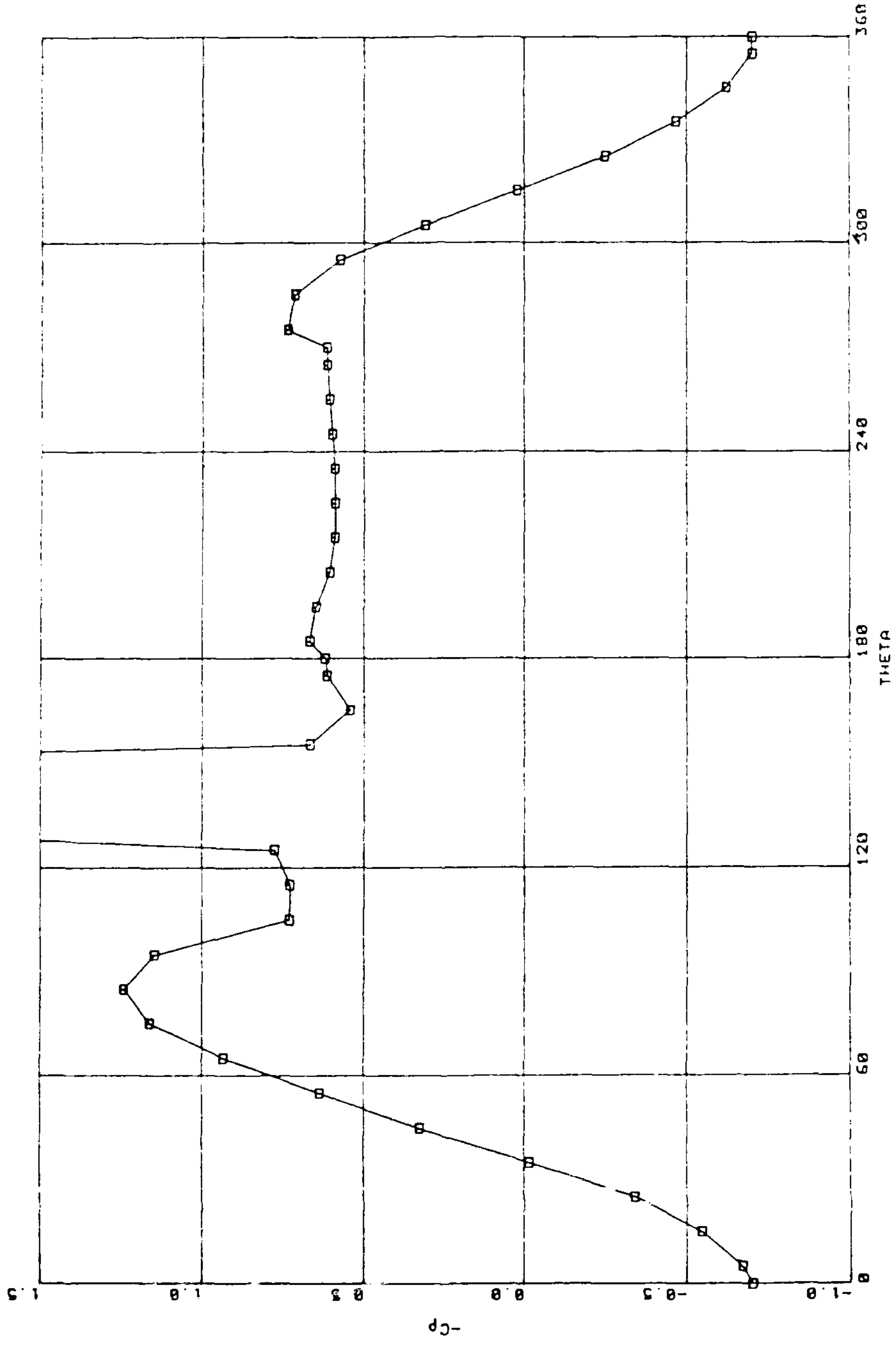

FIGURE 7b Circumferential pressure distribution for 2nd family solution

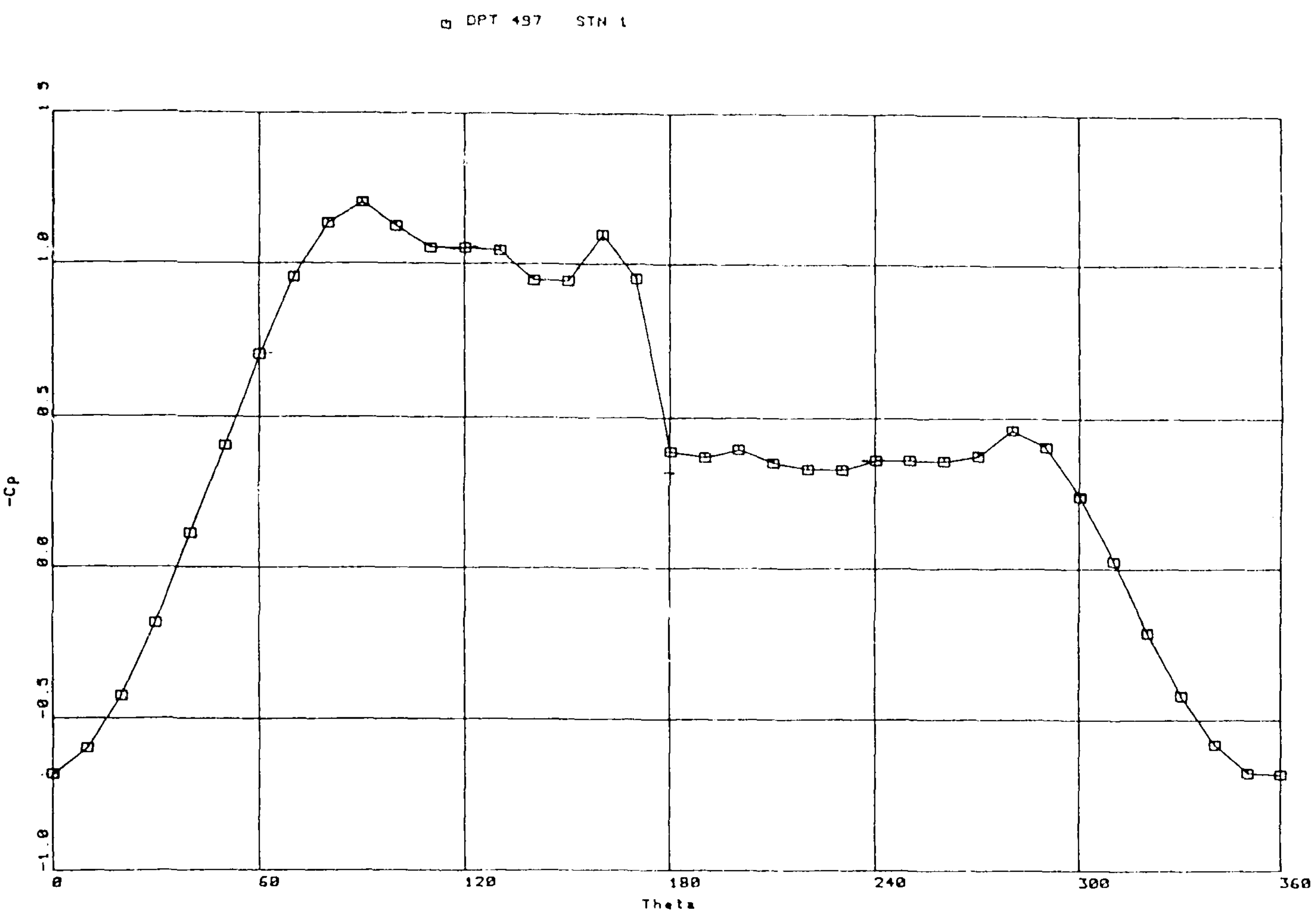

FIGURE 8a Pressure distribution for Incidence = 35 deg., Roll = 100 deg.

Fig 8b

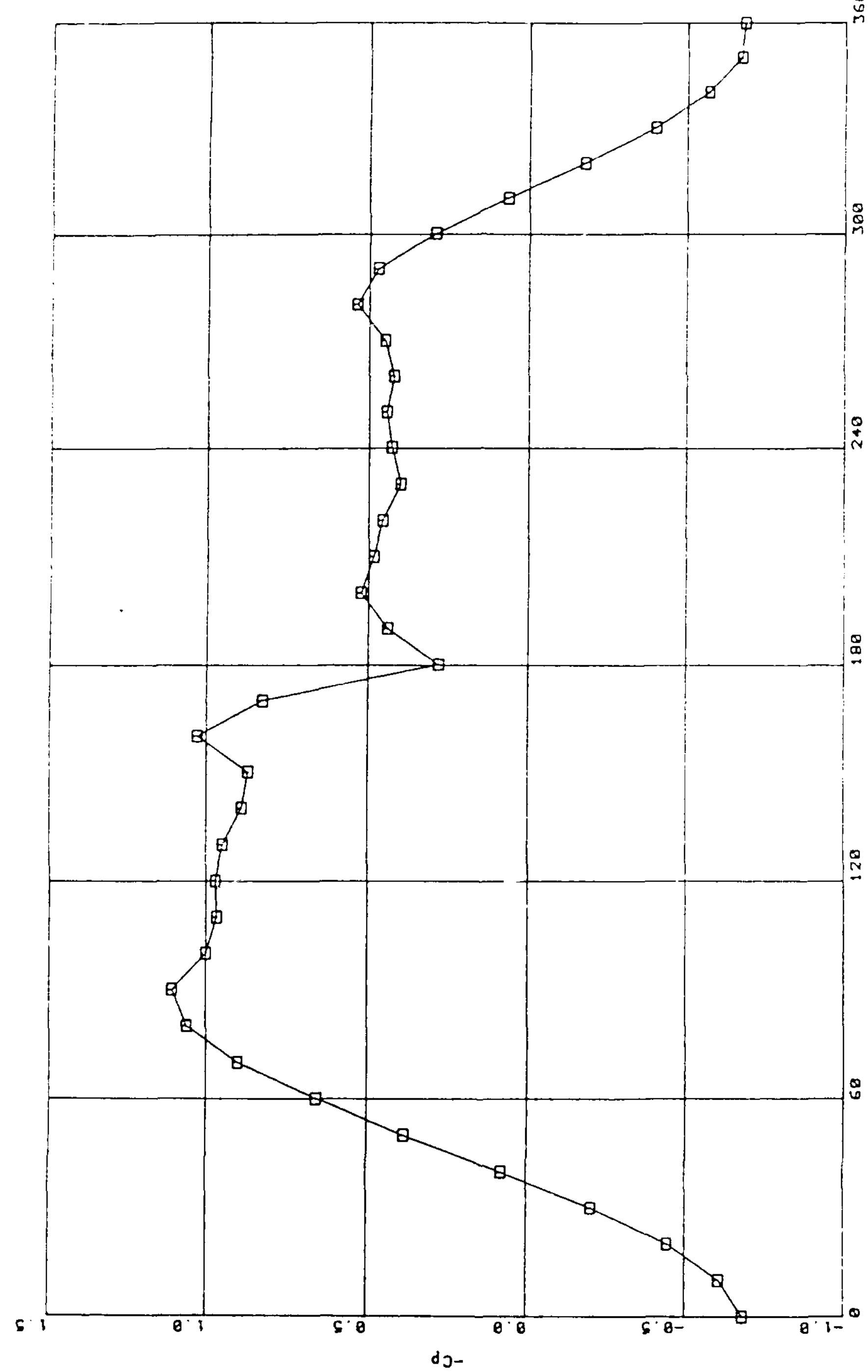

FIGURE 8b Pressure distribution for Incidence = 35 deg., Roll = 110 deg.

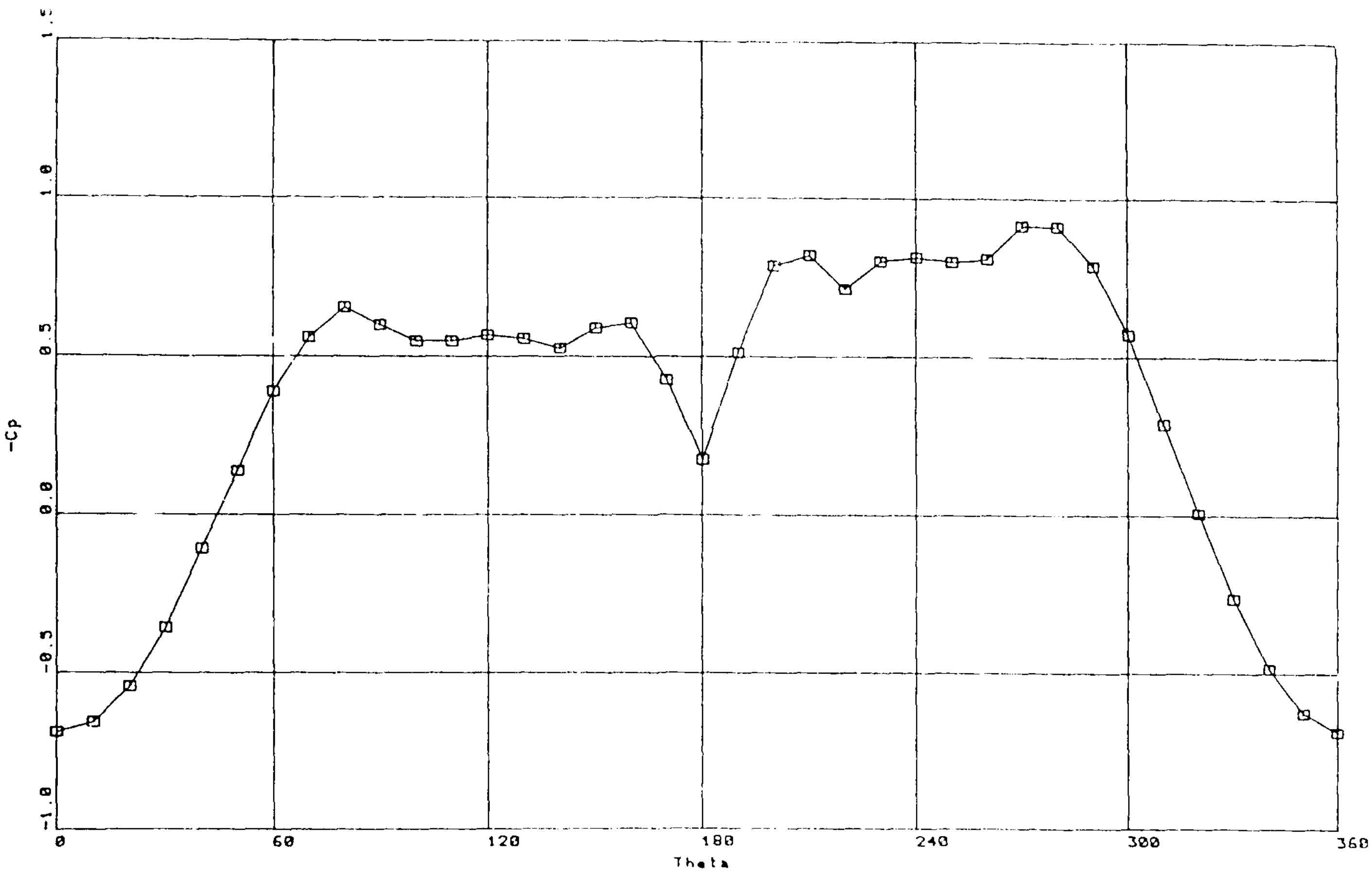

FIGURE 8c Pressure distribution for Incidence = 35 deg., Roll = 120 deg.

Fig 8d

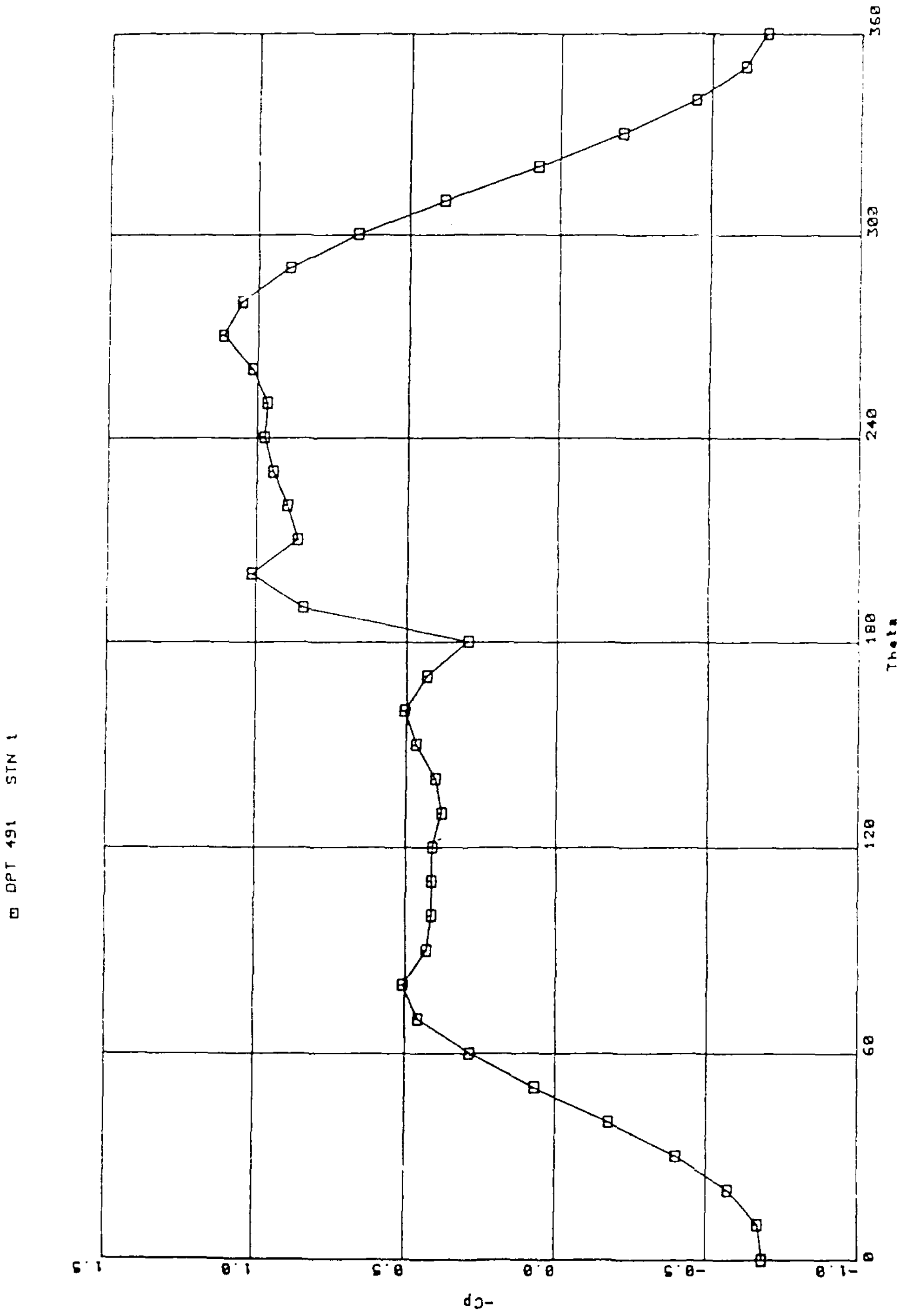

FIGURE 8d Pressure distribution for Incidence = 35 deg., Roll = 130 deg.

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17. Abstract

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